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Test Report: MTR02BPS.001
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Introduction

Two large area (0.94 m^2) CdTe modules (serial nos. 595405 and 595703) were received from BP Solar in May 2002, slated specifically for investigating long-term performance stability versus exposure in an indoor weather chamber (Tenney). The module current-voltage (I-V) characteristics at standard reporting conditions (SRC) were measured at baseline using three separate solar simulator test beds—SPIRE, LACSS and SOMS—performed by the *Cell and Module Measurements and Characterization Team* headed by Keith Emery. These baseline data are summarized below in tabular form. Note that for the LACSS data, dual measurements are performed: one in the as-received storage state and a second taken after 10-min light stabilization at 1-sun, and allowed to cool back down to 25°C. The data in table 1 show that module efficiency is right about 9%. The efficiency data quoted in the right-most column refer to total area values since an aperture was not defined by any frame. Also note that there is little difference between the storage and light-stabilized states at baseline. The eleventh through thirteenth columns (counting from the left) refer to the optimum power point voltage, current and power, respectively. Note that for the SOMS, these data are not normalized to 1000 W/m^2 irradiance.

Table 1. CdTe module baseline performance at standard reporting conditions.

Sample ID	Test Type	Date	Time (MST)	Irradiance (W/m^2)	Temp. (°C)	Voc (V)	Isc (A)	FF (%)	Vmax (V)	Imax (A)	Pmax (W)	Eff. (%)
595405	SPIRE	4/24/2002	11:10:08	1000.0	25.2	44.395	3.118	60.9%	32.189	2.620	84.32	8.92
595405	LACSS	5/7/2002	12:24:18	1000.0	24.9	43.970	2.966	63.0%	32.340	2.539	82.12	8.69
595405	LACSS	5/7/2002	12:57:32	1000.0	25.2	43.830	2.963	63.2%	32.170	2.551	82.07	8.69
595405	LACSS	5/16/2002	16:14:44	1000.0	24.8	43.830	2.989	62.8%	32.280	2.550	82.31	8.71
595405	SOMS	4/17/2002	13:56:08	984.1	23.6	44.300	3.004	63.3%	32.700	2.578	84.29	9.06
595703	SPIRE	4/24/2002	11:05:41	1000.0	25.1	44.623	3.082	62.2%	32.659	2.621	85.59	9.06
595703	LACSS	5/7/2002	13:04:10	1000.0	25.0	44.220	2.919	64.5%	33.390	2.495	83.32	8.82
595703	LACSS	5/7/2002	13:37:58	1000.0	25.3	44.090	2.916	64.6%	33.310	2.493	83.04	8.79
595703	LACSS	5/16/2002	16:21:05	1000.0	24.8	44.130	2.947	64.4%	33.340	2.512	83.74	8.86
595703	SOMS	4/17/2002	13:59:58	972.4	24.1	44.420	2.924	64.5%	33.540	2.497	83.77	9.12

Experiment

The modules were light soaked in the Tenney chamber, which is equipped with a new light source, two metal halide bulbs powered by ballast. The intensity uniformity and spectral content were measured prior to the experiment. The spectral data are depicted in Figure 1 as the integral of the spectral intensity distribution versus wavelength from 350 nanometers (nm) to 950 nm, which covers the useful spectral range for CdTe materials. For comparison, also plotted on Fig.1 is the integral of the AM1.5 global spectrum versus wavelength. For both integrations at any specific wavelength, the values plotted are those integrated from 300 nm up to the wavelength in question. Figure 1 shows that the metal halide lamps' spectral power is fairly well distributed and similar to AM1.5 global spectrum up to about 750 nm. Above 750 nm, the metal halide lamps' spectral intensities underestimate the integrated intensity, which then catches up to AM1.5 above 850 nm, where spectral emission lines from the metal halide lamps occur.

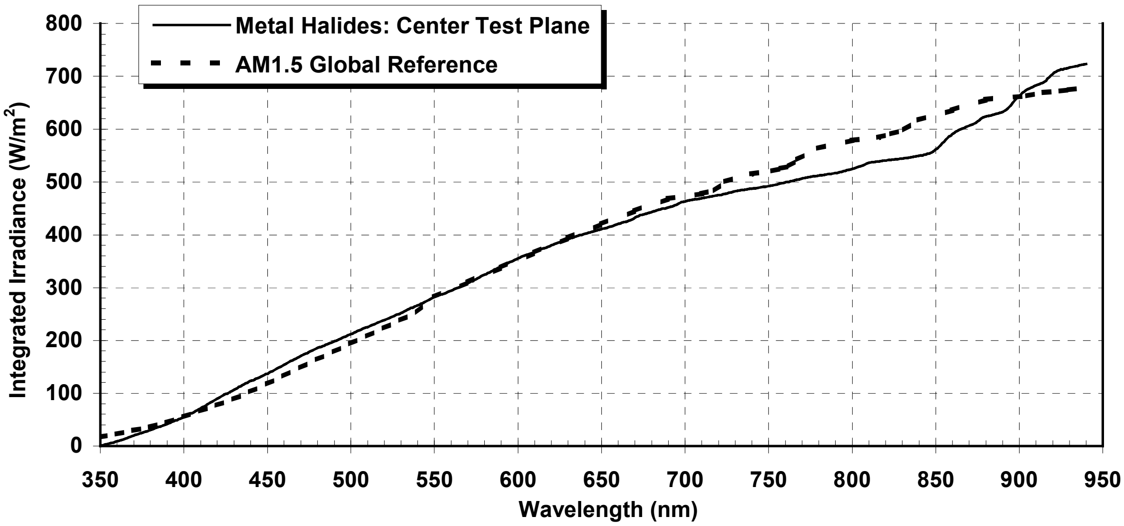

Figure 1. Integrals of the spectral power distributions of the metal halide source and AM1.5 global reference spectrum.

The uniformity of the metal halides lamps is not as good as that for the LACSS or SPIRE simulators. Both modules were situated within a test plane where the average uniformity values varied by ±17.5% above and below average. The irradiance within the chamber was simultaneously sampled at all times with a crystalline silicon (c-Si) detector, an ESTI sensor, which has dual c-Si sensor cells: one for measuring the total irradiance and a second used for calibrating the sensor temperature as a correction to the irradiance measured by the first cell. The ESTI sensor was placed vertically centered in the test plane but just to the left of the modules. By summing the uniformity calibration data and the module positions relative to that data, it was determined that the average light intensities over each module were ±2% of that measured by the ESTI sensor.

Module light soaking was carried out over the course of 5 semesters, between which times the modules were taken down and retested for light and dark I-V characteristics. There were lapses ranging between 2 and 7 days lag between that time when the light-soaking source was turned off and the times the modules were retested. During these storage times, the modules sat under low light level and room temperature conditions. Throughout light exposure, one module was electrically connected to an active electronic load that performed in-situ I-V traces and peak power tracking, while the second one was connected to a fixed resistive load that approximated its optimum power point condition. Also, during the light soaking, module temperatures were sensed using thin-film type 'T' thermocouples bonded to the backsides of each module and just off center. Module temperatures were controlled at nominally 65°±5°C during light soaking. The module temperatures, ESTI sensor temperature and irradiance, air temperature in the chamber, as well as the active electronic load I-V data were interfaced to a data acquisition system (DAS) and sampled at scheduled times throughout the exposure.

Results I: Data at Standard Reporting Conditions

Figure 2 depicts SPIRE data for both modules: the module efficiency and fill factor (FF) data in the upper portion of the graph; the open-circuit voltage (Voc) and short-circuit current (Isc) values from each module are depicted in the bottom portion of the graph; all plotted against exposure time in hours along the ordinate. The hours along the ordinate values are those taken at an average of 822 W/m^2 irradiance. The SPIRE data portray total degradation in performance of about 9%–11% from about 9% efficiency down to about 8%, occurring between baseline and end-of-test (EOT) values in a corresponding time of about 1230 hours exposure. Also, it is evident that the bulk of the degradation occurs during the first 400 hours of light soaking. The degradation is comprised of FF losses ranging 2%–3%; Voc and Isc losses each between 3% and 4%.

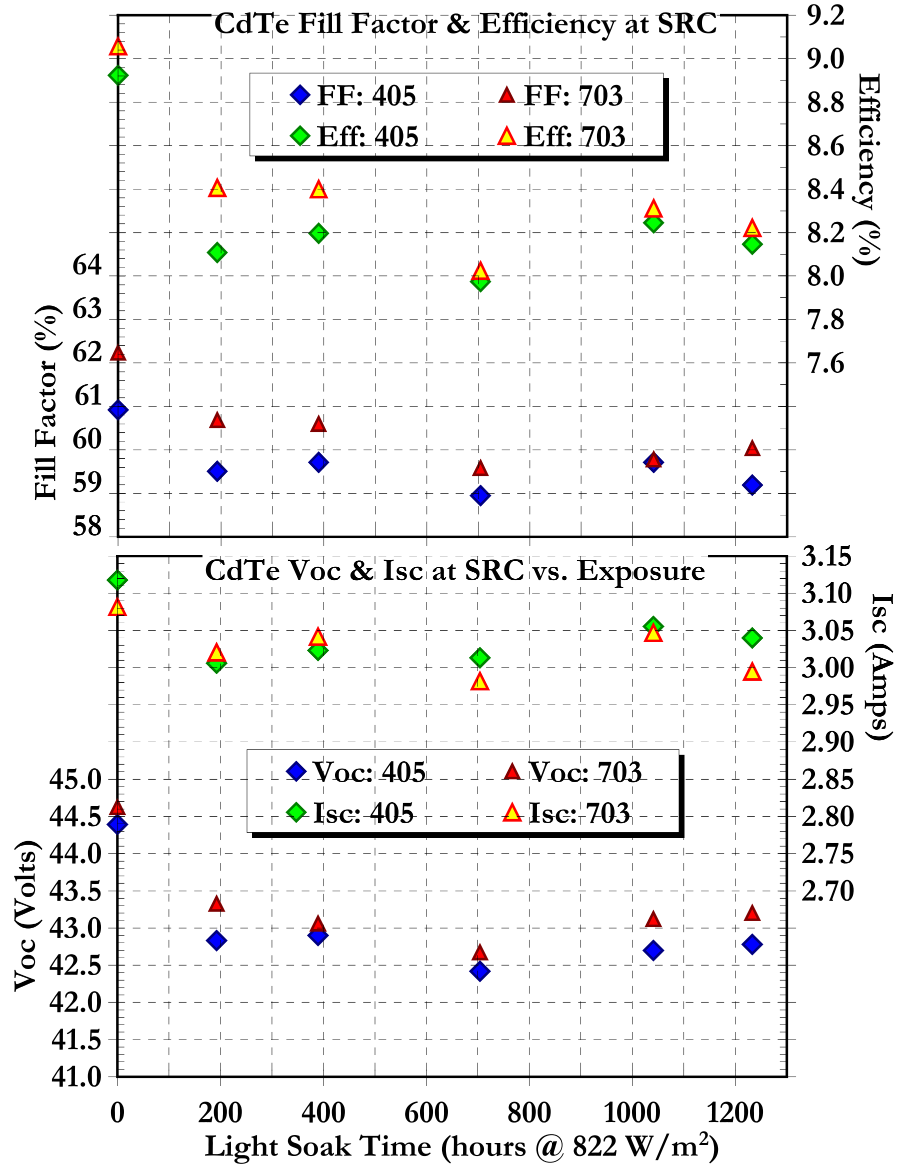

Figure 2. SPIRE I-V data at SRC versus exposure in hours: top part shows efficiency data read from the right-hand abscissa, and FF values read along the left-hand abscissa; bottom part depicts Voc data read along the left-hand abscissa and Isc values data read from the right-hand abscissa.

It is noted that SPIRE data reflect largely storage state values, where the modules have generally been under low light level conditions for at least a day or two prior to testing, except for the points at 700 hours exposure. It that case, the SPIRE data were acquired about an hour after the LACSS data, so that the modules were somewhat light stabilized. For the data taken after roughly 1000 hours exposure and EOT, the storage time lag between light soaking and I-V tests amounts to 3 days. The claim is made that the storage state values may be artificially inflated due to recovery under storage conditions, and that at least for the short times in question that longer storage times lead to greater recovery. The first half of this claim is corroborated by the I-V data collected using the LACSS as shown on Figure 3.

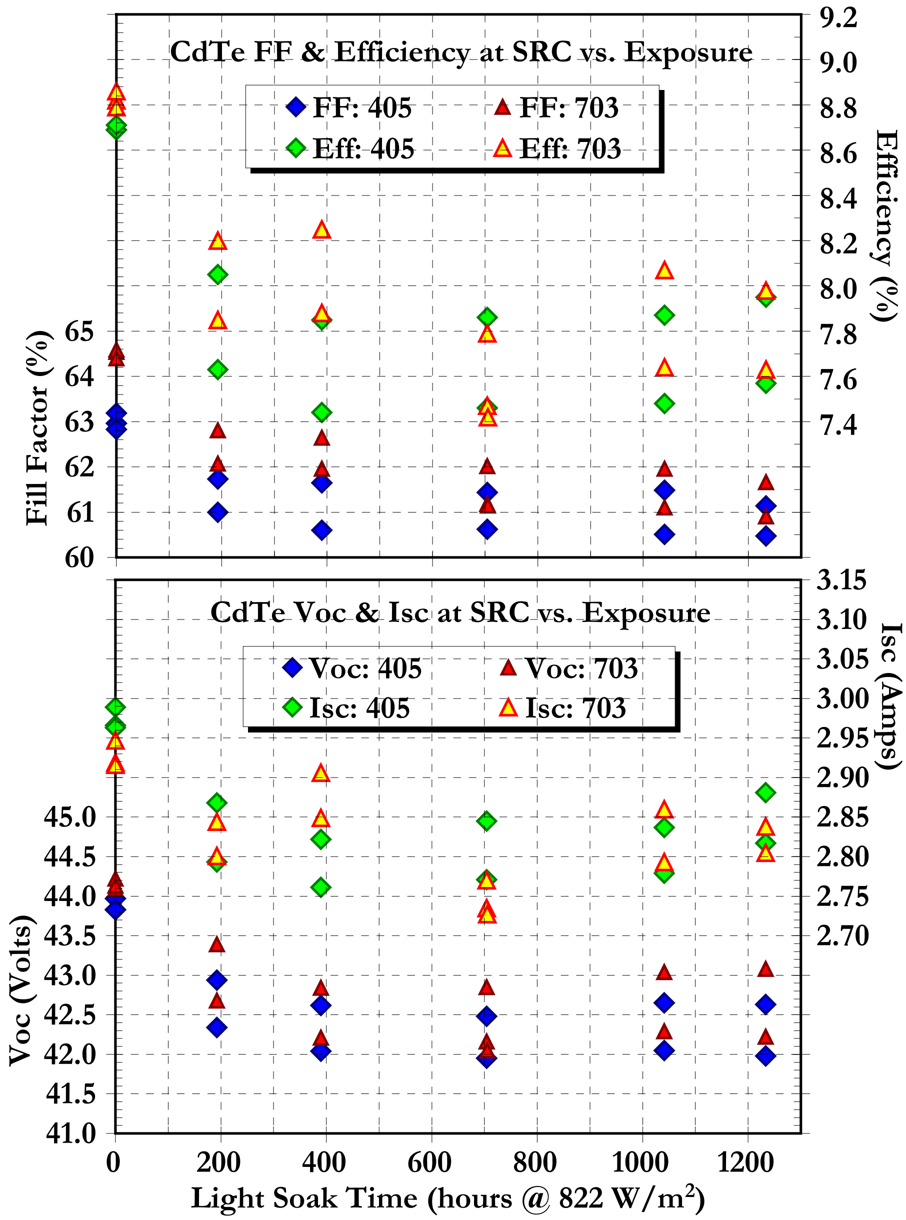

Figure 3. LACSS I-V data at SRC versus exposure in hours: top part shows efficiency data read from the right-hand abscissa, and FF values read along the left-hand abscissa; bottom part depicts Voc data read along the left-hand abscissa and Isc values data read from the right-hand abscissa.

Figure 3 portrays the LACSS I-V data plotted against exposure: the upper portion depicts the efficiency and FF data, while the bottom portion shows the Voc and Isc data. Dual and sometimes triple measurements are shown for all the tests: storage and light-stabilized values. At baseline, there appears to be little difference between storage and light-stabilized values, all module efficiency data fall between 8.7% and 8.9%. However, after exposure, it is evident that light-stabilized efficiency values range 0.4%–0.5% in absolute value lower than storage state values. It appears that FF, Voc and Isc values drop upon light-stabilization by about 1% to 2% each, consistently for every case. Using the LACSS data as a benchmark to gauge changes in module performance, one obtains about 13% to 15% total loss in performance between baseline and EOT values. Also, comparing the SPIRE against the LACSS efficiency data, the storage state values taken on the LACSS (the higher values) are generally quantitatively similar as the SPIRE data but for a shift of about 0.1% –0.2% absolute toward lower values.

Figure 4 shows the dark I-V data taken at various intervals of exposure, for module #405 at top, and #703 at the bottom part of the figure. Using these data, normalized to the cell area of 150.9 cm2, 56 cells in series, the reverse saturation current densities (J_0) are observed to rise from about $3*10^{-7}$ A/cm^2 at baseline, by a multiplicative factor ranging between 7 and 10, up to 2–4*10^{-6} A/cm^2, after 1000 hours of exposure. The apparent diode quality factors, derived from the slopes of the derivative of voltage with respect to current versus the inverse of the current data between 24 and 46 volts, increase from 2.1–2.4 at baseline up to 3.4–3.5 after exposure. The shunt conductance values also appear to increase by about a factor of two from $6*10^{-5}$ to $1.4*10^{-4}$ S/cm^2 for #405, and from $1.4*10^{-4}$ to $3.7*10^{-4}$ S/cm^2 for #703, after 1000 hours of exposure. These increases in shunt may artificially inflate the derived diode quality factors observed after exposure.

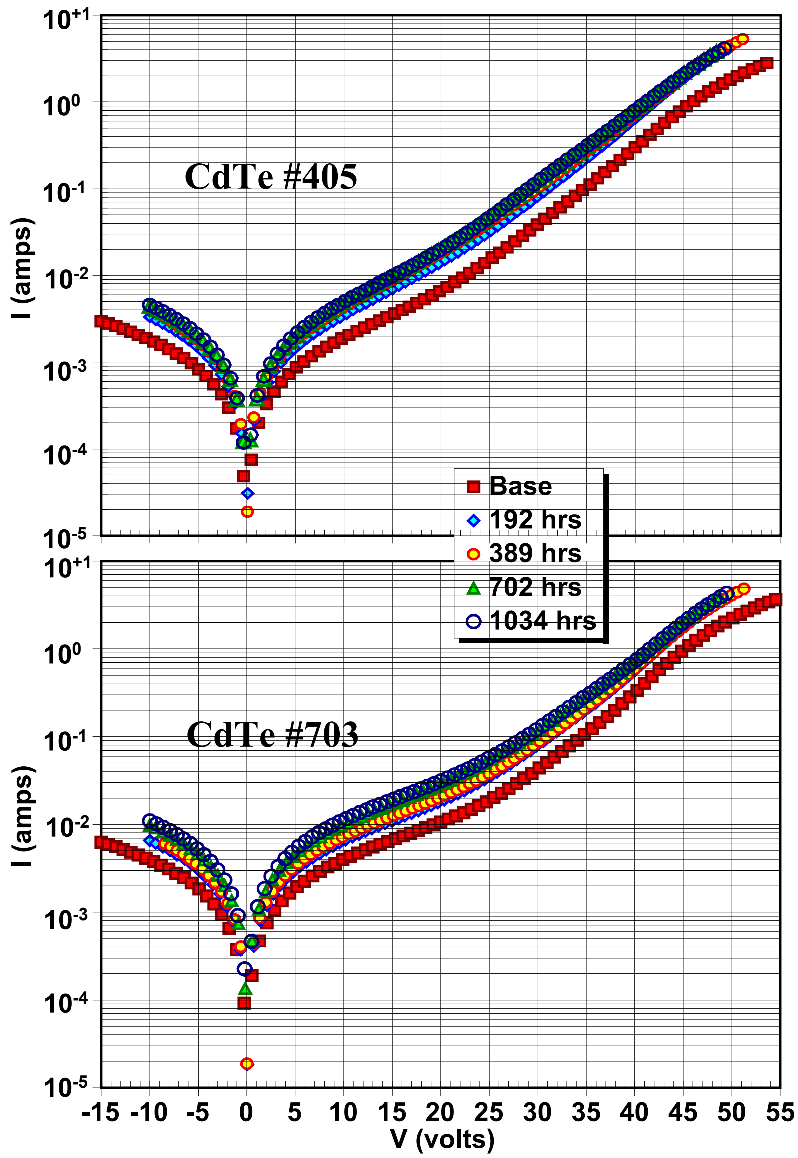

Figure 4. Module #405 (upper) and #703 (lower) dark I-V data measured on the LACSS plotted on a semilog graph of current versus voltage, at various intervals of exposure.

Results II: In-situ Data

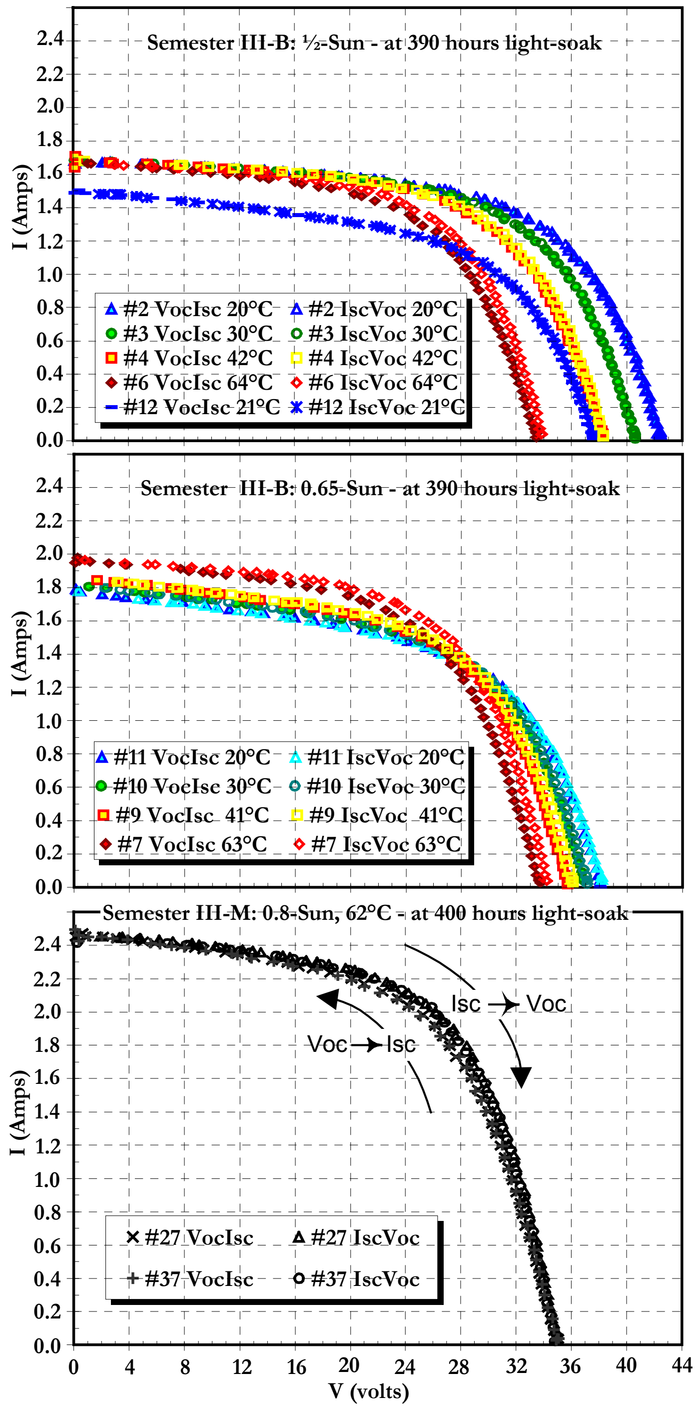

Figure 5. I-V traces for module #703, taken in-situ using programmable electronic load, at various irradiance, times and temperatures in the third semester: 535±2 W/m^2 beginning the semester at top; 650 ±2 W/m^2 beginning the semester in middle; and 833±2 W/m^2 toward mid-semester at bottom.

Figure 5 depicts I-V traces taken sequentially during the third semester using the electronic load and DAS, with each associated to a sequence number such as 2, 3,.., etc. The sequence of traces starts at top, and progresses toward middle and then finally to the bottom. For the top set of curves, traces nos. 2,3,4,6, and 12, the data were measured at 535±2 W/m^2 irradiance and at varying module temperatures, starting at 20°C and increasing to 64°C. The curves are color coded so that blue-end and red-end colors correspond to low and high module temperatures, respectively. Below that in the middle graph, for trace nos. 7 through 11, the irradiance used was set to 650 W/m^2 and the module temperatures lowered from 63°C down to 20°C. Trace #12 in the top graph was taken at 535 W/m^2 irradiance after trace no. 11 in the middle graph. Note the behavior of the set of curves in the top graph, which exhibits the expected decrease of Voc with increasing temperature, yet, an anomalous behavior of Isc with temperature. Indeed for trace #12, the entire curve appears to have shifted downwards in current by about 0.2 amps. These data portray the effects of transient behavior of Isc with time. Such a transient in the top graph is masking both the temperature dependence of Voc and Isc, albeit the middle graph shows more normal behavior.

In the bottom part of Fig. 5, the irradiance is set to 833±2 W/m^2 and temperature is 62°C for two traces spaced 5 hours apart. Even though it appears stable and repeatable, the Isc is actually slowly decaying throughout this time. Also, the FF's measured tracing down from Voc, versus tracing up are consistently different, showing hysteresis, with the downward trace always showing lower FF. This hysteresis appears more readily at the higher module temperatures and only after the module has already been light soaked for a few hundred hours.

Figure 6 depicts I-V measurements taken in-situ with the electronic load for module #703 plotted against exposure time: the module FF data taken while tracing down from Voc to Isc (blue diamonds), and tracing up from Isc to Voc (red squares) along the top part of the graph; and Voc and Isc data on the bottom portion of the graph. The Voc and Isc data reflect measurements in both trace directions as well, but there is little difference between the two sets for these two parameters. None of these data are corrected to a reference temperature, but are restricted to values corresponding to module temperatures between 58° and 66°C. However, the Isc values depicted are normalized to one common mean irradiance value to remove scatter due to any variance in lamp intensity, which averaged 822 ±16.3 W/m^2 for all 5 semesters, where the quoted error reflects ±2 standard variances. Each I-V record consists of dual traces, taken in up and down directions with: about 50 I-V pairs measured in each direction; three analog-to-digital conversions for each measurement of current and voltage; and consistently ~0.78±0.07 secs. time separating bias points.

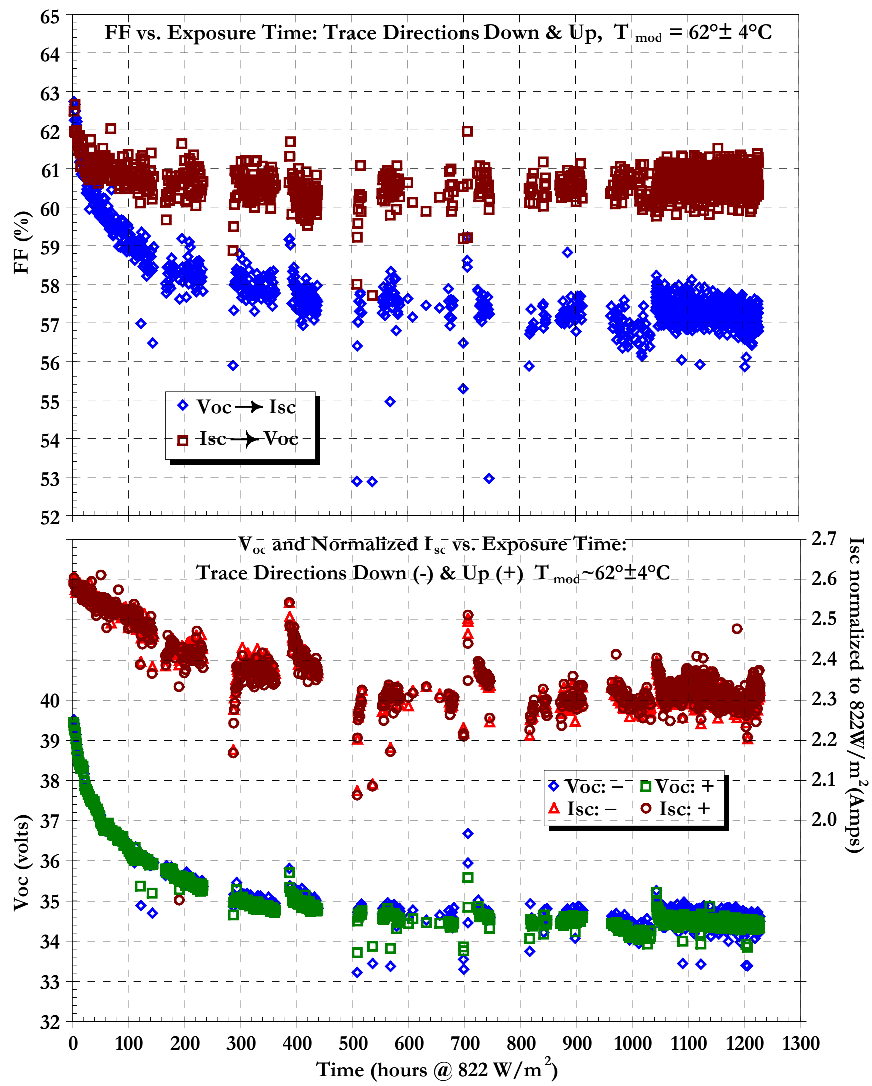

Figure 6. Module #703 I-V data measured in-situ at 822 W/m^2 irradiance and 62°±4°C temperatures plotted against exposure time: FF data on top portion of the graph; Voc data on bottom portion read from left-hand abscissa, Isc data also on bottom portion read from the right-hand abscissa.

Figure 6 shows hysteresis effects on the FF's obtained while tracing down versus tracing up appearing after the first several hundred hours of exposure. At baseline, the FF measured in either direction are similar in value, about ~62.5%. However, after exposure, the FF values obtained while tracing down or up, appear to degrade by about 5% or 2% in absolute terms, respectively. Correspondingly, Voc data exhibit a total degradation of about 5 volts from baseline to EOT values; Isc drops by about 0.3 amps during this time. Also noteworthy is the behavior of Isc immediately following some of the gaps or breaks in the data. Some of these pauses correspond to breaks between semesters, such as at nominally 400 and 700 hours of exposure, between third and fourth semesters, respectively. The Isc values measured at the beginning of the subsequent semester appear to be 0.10–0.15 amps larger the general trend line, and then decay to the trend line after about 10–20 hours of light soaking into the new semester. At other breaks, such as that occurring between 250 and 290 hours of exposure, faults in serial communications between the DAS and the programmable electronic load caused the latter to go into open-circuit. Then for I-V data taken immediately afterwards, the Isc appear to be 0.1–0.15 amps lower then the trend line, a situation that subsequently cures itself after about 10–20 hours when the programmable load goes back to peak-power tracking mode. It is strongly suspected that both these short-time variations in Isc represent daylong transient effects being manifested as result of: 1) recovery followed by degradation occurring immediately following low-light-level storage in the cases between semester breaks; and 2) added degradation followed by recovery after imposition of greater stresses while light soaking inadvertently under open circuit conditions.

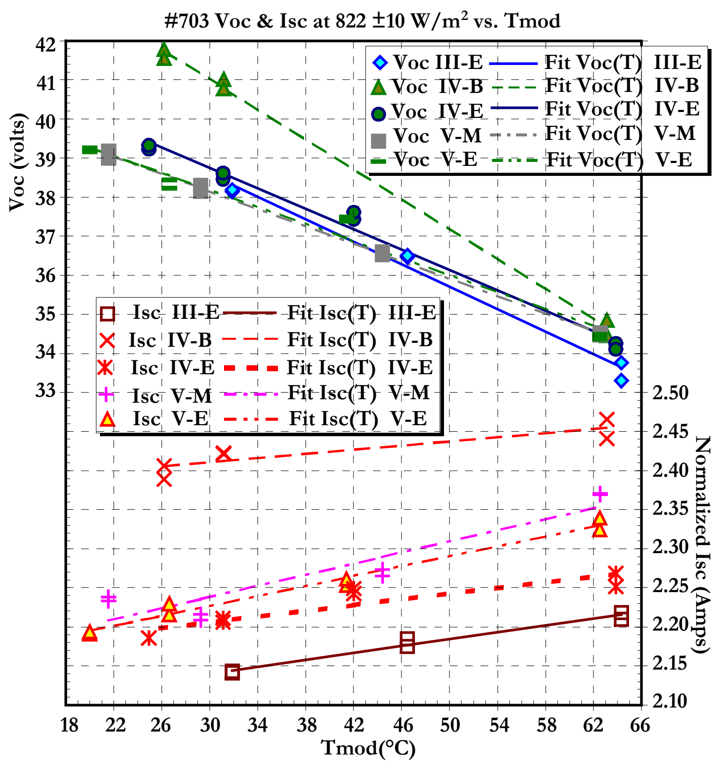

Figure 7. Temperature dependence of Voc and normalized Isc, data plotted along top and bottom portions of the graph, respectively, measured at 822 W/m^2 irradiance during 3rd (III), 4th (IV) and 5th (V) semesters, toward the beginning (B), middle (M) or end (E) of each time period.

The I-V characteristics of module #703 were also measured as a function of module temperature by using the programmable load while in situ, during light soaking.

These data are useful to derive temperature coefficients for Voc and Isc. Figure 7 exhibits the temperature behavior of Voc and normalized Isc obtained at 822±10 W/m^2 irradiance, during various times in the third, fourth and fifth semesters (denoted by the roman numerals III, IV, V), and toward the beginning, middle and end of each of the respective periods. The Isc are normalized to 822 W/m^2, in order to mitigate scatter in the data due to lamp variations. Figure 7 shows that at the beginning of the 4th semester, the Voc and Isc data appear anomalously large especially at the lower temperatures with respect to the rest of the data. Once the temperature was raised to 63°C, the Voc data drop back down to values similar to those obtained at other times; however, the Isc data take a while longer to diminish. In effect the temperature dependence that one measures can be artificially high or low depending on exposure history immediately prior to measurement, due to transient effects. Once the transient effects are gone, the derived linear temperature dependence obtained are more reasonable: for Voc ~ –0.3%/°C, and for Isc between +0.05 and +0.1%/°C.

I-V Measurements at Standard Reporting Conditions and End of Test

The light I-V characteristics measured at SRC and the EOT are tabulated below. These data consists of a set of three separate simulator measurements—SPIRE, SOMS and LACSS—with the LACSS data reflecting both storage and light-stabilized measurements. Going by the LACSS stabilized measurements, there is a total degradation in power output and efficiency of 10–11 watts and 1.1% absolute, respectively. This degradation is comprised of Voc decline of ~1.8–1.9 volts, Isc loss amounting to 0.15–0.17 amps, and FF loss totaling 2%–3% absolute. It is noted that during light soaking, module #405's temperature was typically ~70°C, while that of #703 was close to 63°C.

Table 2. End of Test I-V Parameter Summary.

Sample ID	Test Type	Date	Time (MST)	Irradiance (W/m^2)	Temp. (°C)	Voc (V)	Isc (A)	FF (%)	Vmax (V)	Imax (A)	Pmax (W)	Eff (%)
595405	SPIRE	10/11/2002	12:33:20	1000.0	25.0	42.778	3.0397	59.19%	30.994	2.4834	76.97	8.15
595405	SOMS	10/16/2002	10:32:23	1002.0	20.5	41.840	2.9480	60.30%	30.810	2.4160	74.42	7.86
595405	LACSS	10/15/2002	12:12:56	1000.0	24.9	42.630	2.8810	61.14%	32.200	2.3320	75.10	7.95
595405	LACSS	10/15/2002	12:54:34	1000.0	24.9	41.980	2.8170	60.48%	31.000	2.3070	71.52	7.57
595703	SPIRE	10/11/2002	12:28:31	1000.0	25.0	43.203	2.9950	60.04%	32.403	2.3974	77.68	8.22
595703	SOMS	10/16/2002	10:34:23	1007.7	20.2	42.570	2.9550	60.90%	32.340	2.3690	76.60	8.04
595703	LACSS	10/15/2002	13:00:38	1000.0	25.0	43.080	2.8380	61.66%	32.750	2.3020	75.41	7.98
595703	LACSS	10/15/2002	13:38:54	1000.0	24.9	42.220	2.8050	60.90%	31.900	2.2610	72.12	7.63

Conclusions

Two CdTe modules with baseline efficiency values of ~8.7%–8.8%, and optimum power output of 82–83 watts were light soaked at nominally 65°C temperature and 822±16 W/m^2 irradiance for a total exposure of ~1230 hours. The performance of both modules degrade by about 10.5 to 12 watts after light soaking, with the bulk of the declines occurring during the first 400 hours of light soaking. The modules' performance degrade due to deterioration in Voc, Isc and FF each accounting for between 4% and 5% losses relative to baseline values. Transient effects were observed for both modules, whereby amelioration of both Isc and Voc are evident during storage at low light-level conditions. Hysteresis effects are also manifested in the measurement of module FF at 65°C temperature, after the modules had been soaked for a few hundred hours. These transient effects are likely to affect and confound characterization of module performance as a function of temperature thus impacting the measurement of temperature coefficients of Voc and Isc, even after light soaking.